The Enhancing Effect of Reward on Working Memory Retrieval Accuracy and Its Mechanism

Authors: Niu Hui, Hu Yanmei, Zheng Xutao, Jiang Yingjie, Liu Jia, Yanmei Hu

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Abstract

Accurately retrieving working memory representations according to task demands is of great significance for improving cognitive efficiency. However, the modulating factors and mechanisms underlying the accuracy of working memory retrieval remain unclear. This study takes value-related factors crucial for human survival and development as a starting point, presents reward cues during the working memory retrieval stage, and investigates the reward modulation mechanism in the working memory retrieval process using single retrieval (Experiment 1) and continuous retrieval tasks (Experiment 2). Investigating the reward modulation mechanism in the working memory retrieval process. Experiments 1 and 2 respectively employed single retrieval and continuous retrieval tasks. The present study found that: (1) reward can directly enhance the accuracy of working memory retrieval; (2) the mechanism underlying this facilitative effect of reward is the reallocation of working memory resources; (3) this facilitative effect of reward is influenced by retrieval order and individual differences in working memory capacity. These findings reveal the reward modulation mechanism during the working memory retrieval stage and provide a scientific basis for promoting cognitive efficiency.

Full Text

Reward Facilitates Working Memory Retrieval Accuracy and Its Mechanisms

NIU Hui[1], **HU Yanmei**[1], **ZHENG Xutao**[1], **JIANG Yingjie**[1], **LIU Jia**[1]
([1] School of Psychology, Northeast Normal University, Changchun 130024, China)

Abstract

Accurate retrieval of working memory representations according to task demands is crucial for enhancing cognitive efficiency, yet the factors and mechanisms that modulate working memory retrieval accuracy remain unclear. The present study investigated the reward modulation mechanism during working memory retrieval by presenting reward cues during the retrieval phase, using both single-retrieval (Experiment 1) and continuous-retrieval tasks (Experiment 2). The findings revealed: (1) Reward directly facilitates working memory retrieval accuracy; (2) The facilitating mechanism involves the reallocation of working memory resources; (3) The facilitating effect of reward is influenced by retrieval order and individual differences in working memory capacity. These findings elucidate the reward modulation mechanism during the working memory retrieval stage and provide a scientific basis for promoting cognitive efficiency.

Keywords: working memory, reward, retrieval accuracy

Working memory is essential for human goal-directed behavior and influences human survival and development. During working memory processes, individuals must not only store and process environmental information but also retrieve relevant representations to interact with it (Baddeley, 1992, 2000; Baddeley & Hitch, 1974; Cowan, 2017; Eriksson et al., 2015). The ability to accurately retrieve working memory representations according to task demands is key to effectively advancing goal-directed activities. Therefore, revealing the modulation mechanisms of working memory retrieval accuracy is important for promoting cognitive efficiency and social adaptation. However, previous research addressing this scientific question has been relatively limited.

Reward, which is closely related to value computation, significantly influences human cognition and behavior. For instance, reward can facilitate working memory processing (Atkinson et al., 2018; Beck et al., 2010; Bowen et al., 2020; Gong & Li, 2014; Gong et al., 2016; Hitch et al., 2018, 2020; Kiss et al., 2009; Klyszejko et al., 2014; Lin & Fougnie, 2022; Valentin & O'Doherty, 2009). This facilitating effect can be based either on the enhancement of working memory representations (Gong & Li, 2014; Klink et al., 2017) or on the reallocation of working memory resources (Hitch et al., 2018; Hu et al., 2014). For example, Gong and Li (2014) found that high-reward-associated items were better maintained despite not receiving more spatial attention. Hu et al. (2014) discovered in a serial memory task that when high point values were assigned to the first (or last) item in a sequence, the improvement in its memory performance was accompanied by a reduction in the recency (or primacy) effect. This indicates that reward can guide the reallocation of limited, fixed resources among different items.

However, previous research has primarily focused on the effects of reward on working memory encoding (Allen & Ueno, 2018; Hitch et al., 2018; Hu et al., 2014; Klink et al., 2017; Lin & Fougnie, 2022) and maintenance (Dodgson & Raymond, 2020; Thomas et al., 2016). Studies examining reward modulation during the retrieval stage are scarce and yield controversial results. Most studies present reward signals before the retrieval phase and find that reward can modulate item retrieval (Grogan et al., 2022; Taylor et al., 2004). In contrast, the few studies that present reward signals directly during the retrieval phase find that reward does not affect the retrieval process (Klink et al., 2017). Specifically, Taylor et al. (2004) used fMRI to examine how reward signals appearing during the encoding stage affect working memory encoding, maintenance, and retrieval. They found that reward activated different brain regions across memory stages: ventrolateral prefrontal cortex and precuneus during encoding, frontal and intraparietal sulcus during maintenance, and dorsolateral prefrontal cortex and middle frontal gyrus during retrieval. Grogan et al. (2022) investigated the mechanisms and stages of reward modulation in working memory and found that reward could influence the retrieval process. Participants memorized several items and, after a delay, completed a memory test requiring them to continuously adjust the orientation of a probe stimulus to match the corresponding memory item. By analyzing target selection probability and guessing rates, they could test reward's effect on retrieval. Results showed that reward increased the probability of responses based on target features during retrieval, thereby improving working memory accuracy. However, Klink et al. (2017) found that reward did not affect working memory retrieval. They used a delayed-probe task where participants first memorized three oriented gratings, then probed one memory item randomly during retrieval. Reward cues were three colored rings corresponding to high, low, and no reward, presented at locations matching the memory items. These cues appeared either simultaneously with memory items (encoding stage), during the delay (maintenance stage), or with the probe (retrieval stage). Only when reward cues appeared during encoding did high-reward items show higher memory accuracy; reward signals during maintenance and retrieval did not modulate working memory.

Thus, studies presenting reward signals before retrieval find that reward can modulate working memory processing (Grogan et al., 2022; Taylor et al., 2004), reflecting people's ability to adjust learning strategies based on item value. However, such studies cannot answer whether reward can independently influence working memory retrieval. In daily life, item value is not always predetermined before testing (e.g., during learning or encoding), but often becomes apparent only when testing occurs (e.g., during actual problem-solving or retrieval). Flexibly adjusting retrieval accuracy according to task demands and their changes is crucial for goal-directed behavior. Therefore, presenting reward signals during retrieval—excluding effects from encoding and maintenance—is a more appropriate way to independently examine reward modulation during retrieval. Yet such studies are extremely rare, and their results indicate that reward does not affect retrieval accuracy (Klink et al., 2017), necessitating further empirical verification.

Furthermore, the mechanism of reward modulation during working memory retrieval remains unclear. As mentioned, previous research suggests reward modulation operates through representation enhancement and resource reallocation. However, how reward specifically affects working memory representations and resource allocation during retrieval is unknown. Studies examining retrieval mechanisms have primarily used continuous-retrieval tasks (Myers et al., 2018; Park et al., 2017; Woodman & Vecera, 2011), where participants memorize multiple items and sequentially retrieve each during testing. These studies consistently find that earlier-retrieved items show better performance (Rerko et al., 2014), meaning selectively retrieving one object representation impairs memory accuracy for subsequently reported items. However, views differ on how later-probed item representations are damaged (Park et al., 2017; Woodman & Vecera, 2011). Woodman and Vecera (2011) argued that during continuous retrieval, all maintenance mechanisms focus on the currently retrieved item, damaging memory traces of other items. Park et al. (2017) contended that performance decline for later-probed items results not from reduced representation precision but from complete loss of memory representations. If later-retrieved items merely show reduced precision, reward could improve their accuracy by modulating resource allocation; if their representations are completely lost, retrieval accuracy cannot be modulated. However, studies on reward and working memory retrieval have mainly used single-retrieval tasks, where participants memorize multiple items and one is randomly probed during testing. Such tasks cannot reveal differences in representation precision and resource allocation among items within the same trial. Therefore, continuous-retrieval paradigms are necessary to further examine reward modulation mechanisms during retrieval.

In summary, empirical evidence examining reward modulation during working memory retrieval is scarce and controversial. Most studies introduce reward signals during encoding or maintenance, making it difficult to independently examine reward's effect on retrieval. The few studies presenting reward signals during retrieval require further verification. Additionally, most use single-retrieval tasks, which cannot examine how reward affects retrieval accuracy for different items within the same trial and the differences therein—key to revealing reward modulation mechanisms during retrieval. Therefore, the present study presents reward signals during retrieval, combining single-retrieval (Experiment 1) and continuous-retrieval (Experiment 2) tasks to: (1) further test whether reward can independently modulate working memory retrieval; (2) systematically examine, for the first time, how reward affects representations and resource allocation for different items during continuous retrieval to reveal its mechanism. Additionally, based on findings that cognitive strategy use is influenced by individual working memory capacity (Griffin et al., 2019; Robison & Unsworth, 2017; Turley-Ames & Whitfield, 2003), this study also analyzes individual differences in reward modulation of working memory retrieval.

Experiment 1

Experiment 1 used a single-retrieval task to test whether reward cues appearing during retrieval could facilitate working memory retrieval accuracy. The key variable was the reward level of retrieval cues. If reward can modulate retrieval, accuracy should increase with reward level. Experiment 2 used a continuous-retrieval task with pre- and post-test designs to examine the mechanism of reward facilitation.

Participants sequentially retrieved probe items 1 (T1) and 2 (T2) during testing. The pre-test served as a no-reward baseline. Within each trial, two extraction processes were accompanied by differently colored cues whose colors were unrelated to reward. If cue color itself does not affect retrieval, pre-test performance should only be influenced by retrieval order, with T2 performance worse than T1. The post-test included reward conditions.

The task was identical to the pre-test, but differently colored cues were associated with high and low reward, with high-reward cue location balanced across trials. If reward can eliminate T2's disadvantage, the main effect of probe item should be non-significant, and the interaction between probe item and high-reward cue location should be significant. If reward can only partially improve (rather than eliminate) T2's disadvantage, both the main effect of probe item and the interaction should be significant. If reward does not affect retrieval, only the main effect of probe item should be significant. Regarding mechanism, if reward enhances memory representations, the main effect of high-reward cue location should be significant—meaning average memory performance should be better when high-reward cues accompany T2 versus T1, as the former benefits from both retrieval order and reward while the latter only benefits from retrieval order. Conversely, if reward operates through resource reallocation, high-reward cue location should not affect average memory performance.

Method

Participants Using G*Power software (Faul et al., 2007, 2009), we estimated the required sample size with $\alpha = 0.05$ and $1-\beta = 0.95$. Referencing the effect size of reward effects from Grogan et al. (2022) (^{2}p = 0.21), we set f = 0.52, yielding a minimum sample size of 12. We then recruited 24 university students (7 male, 17 female) aged 18–24 years (M = 21.61, SD = 2.87). Experiment 1 was approved by the Ethics Committee of the School of Psychology at Northeast Normal University. Participants were naïve to the experimental purpose, and compensation was proportional to memory task performance.

Apparatus and Stimuli The experiment was conducted in a dimly lit room with participants seated 57 cm from the screen. The experimental program was written in PsychoPy (Peirce, 2007; Peirce et al., 2019, 2022) and presented on a 19-inch CRT monitor with 1024$×$768 resolution and 120Hz refresh rate.

Association learning stimuli were three circles (5 ° $×$5 ° visual angle) filled with colored noise, presented at 12, 4, and 8 o'clock positions on a virtual circle (radius 5 °) centered on fixation. The three circles were the same color—red (RGB: 255, 0, 0), blue (RGB: 0, 0, 255), or green (RGB: 0, 255, 0).

The working memory test included encoding, delay, and retrieval phases. During encoding, memory stimuli were three oriented circular gratings (approximately 5 ˚ $×$5 ˚ visual angle, contrast 0.5). The three simultaneously presented gratings had different orientations with angular differences $ 15 ˚ .*Memorystimuluslocationsmatchedthoseintheassociationlearningphase.Duringretrieval*, *theprobewas* visual angle) remained on screen from encoding until response completion, positioned to overlap with memory item edges. During encoding and delay, rings were gray (RGB: 128, 128, 128). During retrieval, all three rings simultaneously turned red, blue, or green to provide reward cues.

[Figure 1: see original paper] shows the procedure for Experiment 1 (A) association learning and (B) working memory test phases.

Design and Procedure (1) Association Learning Phase

This phase used a single-factor three-level (reward: high, low, none) within-subjects design. The procedure is shown in [Figure 1: see original paper]A. A blank screen with fixation appeared for 1250–2000 ms, followed by three noise circles of the same color. Noise colors (red, green, blue) corresponded to no reward (+0 points), low reward (+5 points), and high reward (+50 points), respectively. The color-reward association probability was 100%, with correspondence balanced across participants. Participants judged the color and responded via keypress: red = "←", green = "↑", blue = "→" (key-color mapping balanced across participants). Feedback appeared for 1500 ms after response, including response outcome and reward information. Response outcomes were "Correct", "Incorrect", or "Too Slow". "Correct" appeared for accurate responses within 500 ms; "Incorrect" for inaccurate responses; "Too Slow" for responses >500 ms regardless of accuracy. Reward information included (1) current trial points, (2) actual total score, and (3) obtainable total score. Actual total score was the sum of points earned; obtainable total score was the sum possible if all responses were correct. Only correct responses earned reward points, displayed with corresponding dots around the text; incorrect or slow responses showed 0 points with no dots. Ten practice trials preceded 120 experimental trials.

(2) Working Memory Test Phase

This phase used a single-factor three-level (reward: high, low, none) within-subjects design. The procedure is shown in [Figure 1: see original paper]B. A fixation screen appeared for 500 ms, followed by three gratings with different orientations for 1500 ms (to be remembered). Each gring was surrounded by a gray ring that remained until trial end. After a 2000 ms delay, the probe appeared—a randomly oriented grating requiring mouse adjustment to match the remembered orientation at that location. Participants released the mouse and pressed spacebar to confirm. All three memory items had equal probe probability. Simultaneous with probe onset, rings turned red, green, or blue (all three the same color), indicating reward for correct response. Color-value correspondence matched the association learning phase. Feedback lasted 750 ms, including response outcome and reward information. Response outcome was "Correct" if reported angle differed from target by <15°, otherwise "Incorrect". Reward information matched the association learning phase. Ten practice trials preceded 120 experimental trials.

Experiment 1 lasted approximately 30 minutes, with rest breaks after every 40 trials in both phases.

Results

Data were analyzed using R 3.6.2 and JASP 0.16.4. Data beyond $±$3 standard deviations were excluded (<1% in Experiment 1; <2% in Experiment 2). In the association learning phase, accuracy and reaction time were analyzed via one-way repeated-measures ANOVA to test color-value association establishment. In the test phase, angular deviation (absolute difference between reported and target angles) served as the dependent measure of memory accuracy. Differences across reward conditions were examined to assess reward effects. All multiple comparisons across three levels used Bonferroni correction (Dunn, 1961).

Association Learning Phase One-way three-level (reward: high, low, none) repeated-measures ANOVAs on accuracy and reaction time revealed significant reward effects. For accuracy: F(2, 46) = 4.14, p = 0.022, ^{2}p = 0.15, BF10 = 3.604. Pairwise comparisons showed marginally significant differences between high-reward (M = 0.92) and no-reward (M = 0.86) conditions (t(23) = 2.45, p = 0.066, Cohen's d = 0.57). No significant differences between high- and low-reward (M = 0.90) or low- and no-reward conditions (ps $\geq$ 0.24). For reaction time: F(2, 46) = 13.21, p < 0.001, ^{2}p = 0.37, BF10 = 853.416. High-reward responses (M = 421.58 ms) were significantly faster than low-reward (M = 447.00 ms) and no-reward (M = 462.96 ms) conditions (t(23) = –2.92 & –4.85, p = 0.023 & p < 0.001, Cohen's d = 0.64 & 1.04). Low- and no-reward conditions did not differ significantly (t(23) = 2.28, p = 0.098, Cohen's d = 0.40) (see [Figure 2: see original paper]A). These results indicate successful color-reward association learning.

Working Memory Test Phase One-way three-level (reward: high, low, none) repeated-measures ANOVA on angular deviation revealed a significant main effect: F(1, 23) = 6.52, p = 0.003, ^{2}p = 0.22, BF10 = 13.297 (see [Figure 3: see original paper]). Angular deviation was significantly larger in the no-reward condition (M = 21.20°) than in high-reward (M = 16.74°) and low-reward (M = 17.65°) conditions (t(23) = 3.42 & 2.72, p = 0.004 & 0.027, Cohen's d = 0.74 & 0.59). High- and low-reward conditions did not differ significantly (t < 1). These results indicate that reward signals presented during retrieval improve working memory retrieval accuracy, primarily distinguishing reward from no-reward conditions. The difference between high and low reward requires further examination, as does the underlying mechanism.

Experiment 2

Experiment 1 demonstrated that reward facilitates working memory retrieval accuracy, with rewarded conditions outperforming no-reward conditions, though high- versus low-reward differences were non-significant. Experiment 2 further examined this difference and investigated mechanisms using continuous retrieval and pre/post-test designs. Experiment 2 comprised four phases: pre-test, association learning, post-test, and confidence judgment. The pre-test (no reward) established baseline performance for retrieval order effects. The post-test (with reward) examined how reward affects memory representations for early- and late-retrieved items and the underlying mechanism. If reward can modulate continuous retrieval, its improvement for late-retrieved items may exceed its facilitation for early-retrieved items. Regarding mechanism, if reward enhances representations, better performance should occur when high-reward items are retrieved later. If reward operates via resource reallocation, retrieval order of high-reward items should not affect average performance. Additionally, given that reward effects may be moderated by individual capacity (Griffin et al., 2019), we differentiated participants by pre-test performance to examine individual differences. The confidence judgment phase assessed participants' ability to predict the second cue's color from the first, testing cue-order expectations.

Method

Participants Using G*Power with $\alpha = 0.05$, $1–\beta = 0.95$, and the same effect size from Grogan et al. (2022) (^{2}p = 0.21, f = 0.52), the minimum sample size was 12. To examine individual differences, we recruited 60 university students (18 male, 42 female) aged 18–26 years (M = 22.70, SD = 2.10). The top and bottom 30% of pre-test performers were designated as high- and low-capacity groups (n = 18 each). Experiment 2 was approved by the Ethics Committee, participants were naïve to the purpose, and compensation was performance-based.

Apparatus and Stimuli Apparatus and stimuli were identical to Experiment 1 except: (1) Association learning stimuli were reduced to two colored noise circles presented at 3 and 9 o'clock positions (blue or green); (2) Working memory test stimuli (pre- and post-test) included two oriented gratings at these same locations, with two sequentially presented probe gratings (one per side, location order balanced across trials); (3) Cue stimuli were blue or green rings surrounding probes, with colors balanced across trials.

[Figure 4: see original paper] shows the procedure for Experiment 2 pre-test and post-test phases.

Design and Procedure **(1) Pre-test Phase**
Cue colors were reward-unrelated. Cues were designated neutral cue 1 and 2, corresponding to high- and low-reward colors in later phases. Probe items were designated first (T1) and second (T2) based on retrieval order. Neutral cue 1

location was SP1 when accompanying T1, SP2 when accompanying T2. The pre-test used a 2 (neutral cue 1 location: SP1, SP2) × 2 (probe item: T1, T2) within-subjects design.

The procedure matched Experiment 1's test phase except: fixation (500 ms), two gratings to remember (1500 ms), 2000 ms delay, then two sequential memory tests per trial. Each probe appeared with a reward cue (blue or green ring). Cue colors differed within a trial. Feedback appeared after both probes, showing response outcomes ("Correct"/"Incorrect") for each location. Ten practice trials preceded 120 experimental trials. To prevent cue-order prediction, 24 filler trials were added where both cues were identical (12 all-blue, 12 all-green).

(2) Association Learning Phase
This phase matched Experiment 1 except: only blue (high reward, +50 points) and green (low reward, +5 points) stimuli were used. Green = "←", blue = "→" (mapping balanced). Ten practice trials preceded 120 experimental trials.

(3) Post-test Phase
Cue colors were reward-associated, matching the learning phase. High-reward cue location had two levels (SP1, SP2), creating a 2 (high-reward cue location: SP1, SP2) × 2 (probe item: T1, T2) within-subjects design.

The procedure matched the pre-test except: feedback was two-screen. Screen 1 showed response outcome and trial points for each location (with dots for correct responses). Screen 2 showed cumulative actual and obtainable total scores (sum of both items). Ten practice trials preceded 240 experimental trials and 48 filler trials (24 all-blue, 24 all-green).

Experiment 2 lasted approximately 90 minutes, with breaks every 48 trials (pre-test), 40 trials (learning), and 72 trials (post-test).

(4) Confidence Judgment
After the experiment, participants rated their confidence (1–7 scale) in predicting the second cue's color from the first cue (7 = "completely confident", 1 = "not confident at all").

Results

Data were analyzed using R 3.6.2 and JASP 0.16.4 with the same exclusion criteria. One participant performing >3 SD below the mean was excluded, leaving 59 valid datasets.

(1) Association Learning Phase
One-way ANOVA on high- versus low-reward conditions showed no accuracy difference ($F(1, 58) = 2.21$, $p = 0.142$, $^{2}p = 0.04$, BF10 = 0.557). Reaction time showed a significant reward effect: $F(1, 58) = 27.99$, $p < 0.001$, $^{2}p = 0.33$, BF10 > 1000, with faster responses for high-reward (M = 385.37 ms) versus low-reward (M = 406.09 ms) (see [Figure 2: see original paper]B), confirming successful color-reward association.

(2) Working Memory Test Phase
Angular deviation served as the accuracy measure. Pre-test data were analyzed with 2 (neutral cue 1 location: SP1, SP2) × 2 (probe item: T1, T2) repeated-measures ANOVA. Probe item main effect was significant: F(1, 58) = 66.95, p < 0.001, ^{2}p = 0.54, BF10 > 1000. T2 deviation (M = 15.00°) was significantly larger than T1 (M = 10.96°), showing better performance for early-retrieved items. Neutral cue 1 location main effect (F < 1, BF10 = 142) and interaction (F(1, 58) = 2.42, p = 0.125, ^{2}p = 0.04, BF10 = 0.328) were non-significant (see [Figure 5: see original paper]A), indicating later-retrieved items were impaired by earlier retrieval.

To confirm cue combination effects, filler trial data were analyzed comparing four cue-combination conditions. One-way ANOVA showed no effect of cue combination on average memory performance (F < 1, BF10 = 0.031), confirming that cue color did not influence performance.

Post-test data were analyzed with 2 (high-reward cue location: SP1, SP2) × 2 (probe item: T1, T2) repeated-measures ANOVA. Probe item main effect was significant: F(1, 58) = 97.58, p < 0.001, ^{2}p = 0.63, BF10 > 1000, with larger T2 deviation (M = 11.17°) than T1 (M = 9.78°). High-reward cue location main effect was non-significant (F(1, 58) = 1.67, p = 0.202, ^{2}p = 0.03, BF10 = 0.204). The interaction was significant: F(1, 58) = 9.00, p = 0.004, ^{2}p = 0.13, BF10 = 84.711. Simple effects showed: for T1, SP1 (M = 9.57°) outperformed SP2 (M = 9.99°) (t(58) = –2.33, p = 0.023, Cohen's d = 0.30); for T2, SP1 (M = 11.55°) was worse than SP2 (M = 10.78°) (t(58) = 2.69, p = 0.009, Cohen's d = 0.35) (see [Figure 5: see original paper]B). These results indicate that although later-retrieved items remained impaired overall, high-reward cues facilitated both early- and late-retrieved items. The non-significant high-reward cue location main effect suggests resource reallocation as the modulation mechanism.

Post-test filler trials were analyzed comparing four reward-cue combination conditions. One-way ANOVA showed no effect of cue combination (F(3, 174) = 0.57, p = 0.636, ^{2}p = 0.01, BF10 = 0.041), further supporting that average memory performance was unaffected by high/low reward cue combinations, consistent with resource reallocation theory.

(3) Pre-test vs. Post-test Comparison
Facilitation magnitude was calculated as pre-test minus post-test scores (pre-test neutral cues 1/2 corresponded to post-test low/high reward conditions). A 2 (high-reward cue location: SP1, SP2) × 2 (probe item: T1, T2) repeated-measures ANOVA on facilitation showed significant probe item main effect: F(1, 58) = 23.66, p < 0.001, ^{2}p = 0.29, BF10 > 1000, with greater facilitation for T2 (M = 3.83°) than T1 (M = 1.17°). High-reward cue location main effect was non-significant (F(1, 58) = 1.07, p = 0.305, ^{2}p = 0.02, BF10 = 0.168). The interaction was significant: F(1, 58) = 8.61, p = 0.005, ^{2}p = 0.13, BF10 = 2.670. Simple effects showed: for T1, SP1 (M = 1.52°) and SP2 (M = 0.83°) differed significantly (t(58) = 2.30, p = 0.025, Cohen's d = 0.30); for T2, SP1 (M = 3.21°) and SP2 (M = 4.44°) differed significantly (t(58) = –2.41, p = 0.019,

Cohen's d = 0.31) (see [Figure 6: see original paper]). These results indicate that high-reward cues facilitated both early- and late-retrieved items, but more strongly for late-retrieved items.

A 2 (high-reward cue location: SP1, SP2) × 2 (probe item: T1, T2) × 2 (capacity: high, low) repeated-measures ANOVA on facilitation showed non-significant high-reward cue location main effect (F(1, 34) = 1.53, p = 0.225, ^{2}p = 0.04, BF10 = 0.215). Probe item main effect was significant: F(1, 34) = 20.96, p < 0.001, ^{2}p = 0.38, BF10 > 1000. Capacity main effect was significant: F(1, 34) = 29.71, p < 0.001, ^{2}p = 0.47, BF10 > 1000, with greater facilitation for low-capacity (M = 5.19°) versus high-capacity (M = 0.56°) groups. Two-way interactions between high-reward cue location × probe item and probe item × capacity were significant (F(1, 34) = 7.55 & 11.53, p = 0.010 & 0.002, ^{2}p = 0.18 & 0.25, BF10 = 1.429 & BF10 > 1000). High-reward cue location × capacity interaction was non-significant (F(1, 34) = 2.07, p = 0.159, ^{2}p = 0.06, BF10 = 0.309). The three-way interaction was significant: F(1, 38) = 5.05, p = 0.031, ^{2}p = 0.13, BF10 = 1.038. Simple effects in the high-capacity group showed significant probe item effect (F(1, 17) = 5.60, p = 0.030, ^{2}p = 0.25, BF10 = 3.978) but non-significant high-reward cue location effect and interaction (Fs < 1, BF10 = 0.240 & 0.412). In the low-capacity group, probe item effect was significant (F(1, 17) = 16.95, p < 0.001, ^{2}p = 0.50, BF10 > 1000); high-reward cue location effect was non-significant (F(1, 17) = 2.28, p = 0.149, ^{2}p = 0.12, BF10 = 0.306); and the interaction was significant (F(1, 17) = 7.46, p = 0.014, ^{2}p = 0.31, BF10 = 2.147). Simple effects showed: for T1, SP1 (M = 2.95°) and SP2 (M = 1.76°) did not differ (t(17) = 1.57, p = 0.146, Cohen's d = 0.36); for T2, SP1 (M = 6.59°) and SP2 (M = 9.42°) differed significantly (t(17) = –2.62, p = 0.018, Cohen's d = 0.62) (see [Figure 7: see original paper]). These results indicate that in the high-capacity group, reward facilitation was modulated by probe order but not high-reward cue location. In the low-capacity group, reward facilitation was more evident during second retrieval.

(4) Confidence Judgment

Mean confidence rating was 3.53, significantly below the midpoint of 4 ("uncertain") (t(59) = –2.71, p = 0.009), indicating participants could not predict the second cue's color.

Discussion

This study investigated how reward signals presented during retrieval affect working memory retrieval and its mechanisms. First, both experiments found that reward directly influences working memory retrieval accuracy. In Experiment 1, high- and low-reward conditions (though not significantly different from each other) outperformed no-reward. Experiment 2's post-test interaction confirmed that high-reward cues improved retrieval accuracy more than low-reward cues.

Second, Experiment 2 found reward affected late-retrieved items (T2) more than early-retrieved items (T1). Pre/post-test comparisons showed greater facilitation magnitude for T2, indicating reward primarily ameliorated the disadvantage of late retrieval rather than eliminating it.

Third, reward modulation was influenced by individual working memory capacity. In the high-capacity group, reward facilitation was affected by probe order but not high-reward cue location. In the low-capacity group, reward facilitation was influenced by the interaction of probe order and high-reward cue location.

This study is the first to observe that reward can directly modulate working memory retrieval without affecting encoding and maintenance. This indicates individuals can adjust cognitive strategies before/during learning based on item value to promote working memory processing (Dodgson & Raymond, 2020; Hitch et al., 2018, 2020; Hu et al., 2014; Klink et al., 2017; Lin & Fougnie, 2022; Sandry & Ricker, 2020; Thomas et al., 2016), and can also adjust retrieval precision after learning based on test-established value information. This flexible working memory regulation mechanism is important for promoting human cognitive activities and social adaptation. However, these findings differ from Klink et al. (2017), who found retrieval-phase reward cues did not affect working memory. This discrepancy may relate to task complexity. Both Experiment 1 and Klink et al. used single-retrieval tasks with similar probes, but differed in cue presentation: Klink et al. simultaneously presented high, low, and no-reward cues, while Experiment 1 presented only one reward level per screen. Our design may better enable reward effects by allowing participants to allocate resources based on current cue value without requiring inter-item allocation within a display. Alternatively, this may suggest reward's effect on retrieval accuracy is global and cannot be further spatially allocated based on item value—an hypothesis for future research.

Regarding mechanism, reward modulation during retrieval generally involves resource reallocation, while being influenced by retrieval position and individual capacity. Previous research shows early-retrieved items automatically enter the focus of attention, impairing representations of later items (Park et al., 2017; Woodman & Vecera, 2011). If reward modulation during retrieval involved allocating additional resources to high-reward items without affecting low-reward representations, then retrieving high-reward items later should yield better performance (SP2 > SP1). Experiment 2 results contradict this hypothesis: overall, retrieval accuracy was unaffected by high-reward cue location. Moreover, filler trial analyses showed no effect of high/low reward cue combinations on average memory performance. Thus, reward modulation during retrieval involves reallocating fixed, limited resources among items based on value (Hitch et al., 2018; Hu et al., 2014; Sandry & Ricker, 2020).

Retrieval position effects show that reward facilitates late-retrieved items more. Although Experiment 2's post-test showed early-retrieved items consistently outperformed late-retrieved items (reward did not reverse this disadvantage), reward's greater impact on late items was evident in the larger facilitation magnitude for T2. This also provides an alternative explanation for the discrepancy with Klink et al. (2017): their single-retrieval task may have made reward modulation less detectable, whereas Experiment 2's dual-retrieval task revealed reward's effect more prominently during second retrieval.

Finally, reward modulation is moderated by individual working memory capacity, with lower-capacity individuals more susceptible to reward effects. In the high-capacity group, reward facilitated T2 more than T1, independent of high-reward cue location, suggesting they had sufficient resources for high-precision representation of all items and could improve late-retrieval disadvantage without value-based strategy adjustments. Griffin et al. (2019) similarly found high-capacity individuals showed only weak selective preference for high-value word pairs. In the low-capacity group, reward facilitation was influenced by the interaction of probe order and high-reward cue location: high-reward cues did not facilitate T1 more than low-reward cues, but facilitated T2 significantly more. Overall, high-reward cue location did not affect average memory performance, indicating low-capacity individuals are more sensitive to reward value changes, with modulation following resource reallocation mechanisms. Previous research indicates individuals maximize benefits by using more effective encoding strategies, particularly low-capacity individuals (Turley-Ames & Whitfield, 2003), though some suggest low-capacity individuals spontaneously use effective strategies less frequently (Robison & Unsworth, 2017). Experiment 2's low memory load (two items) may have obscured reward modulation in the high-capacity group; future research should examine interactive effects of memory load and individual capacity on reward modulation.

In conclusion, through resource reallocation, reward can directly facilitate working memory retrieval accuracy without affecting encoding and maintenance. During continuous retrieval, this facilitation is stronger for late-retrieved than early-retrieved items, and individuals with lower working memory capacity are more susceptible to reward modulation.

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Reward Facilitates Working Memory Precision during Retrieval

NIU Hui[1], HU Yanmei[1], ZHENG Xutao[1], JIANG Yingjie[1], LIU Jia[1]
([1] School of Psychology, Northeast Normal University, Changchun 130024, China)

Abstract

Reward can improve working memory performance. However, controversy exists regarding whether reward can regulate working memory retrieval. Some studies presenting reward signals before retrieval show reward affects retrieval, while Klink et al. (2017) found retrieval-phase reward cues ineffective. This finding lacks replication and requires further testing. The present study explores reward's mechanism and effect on working memory precision during retrieval.

Twenty-four participants (Experiment 1) and 60 participants (Experiment 2) completed two experiments. Experiment 1 included association learning and memory test phases. Participants first learned color-value associations, then completed a working memory test where reward cues accompanied memory probes. Experiment 2 included pre-test, association learning, post-test, and confidence assessment phases. Pre- and post-tests required sequential memory retrieval, with reward-unrelated cues in the pre-test and reward-associated cues in the post-test. Confidence judgment assessed participants' ability to predict the second cue from the first.

Experiment 1 showed significant reward effects: high- and low-reward cue memory performance exceeded no-reward performance. Experiment 2's post-test revealed significant test order effects (first test item > second test item) and a significant test order × high-reward cue location interaction. First-item performance was better when high-reward preceded low-reward cues; second-item performance was better when low-reward preceded high-reward cues. Participants were divided by pre-test performance to examine individual differences. Reward did not affect high-capacity participants' memory performance. Low-capacity participants' performance was affected by test order, high-reward cue location, and their interaction, showing more pronounced reward effects.

This study first observed that reward can directly regulate working memory retrieval without affecting encoding or maintenance. The mechanism involves redistribution of working memory resources, moderated by test order and working memory capacity. Individuals can adjust cognitive strategies before/during learning based on item value and can adjust retrieval precision after learning based on test-established value information. This flexible working memory regulation mechanism is important for human cognitive activities and social adaptation.

Keywords: working memory, reward, retrieval precision

Note: Figure translations are in progress. See original paper for figures.